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Cognitive radio sensor networks: Smart communication for smart grids—A case study of Pakistan

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ABSTRACT

A smart grid has recently gained significant attention as it is an important direction of power system advancement. The integration of renewable energy (RE) resources to the power system and the reduction of energy losses need an efficient and low-cost communication infrastructure. Cognitive radio sensor networks (CRSN) can be integrated in a smart grid to meet these challenges. CRSN is a new paradigm of research where the best of wireless sensor networks (WSN) and cognitive radios (CR) is combined. The sensor networks monitor a physical parameter and the measures value is transmitted using the cognitive radio. Thus, CRSN can be used for realizing the sensing and communication part in a smart grid network. In this paper, a smart grid network is proposed using CRSN for implementing it in the remote areas of Pakistan. The service coverage map is taken from the Pakistan Telecommunication Authority (PTA) website that regulates the spectrum band in Pakistan. This can be used in developing countries to realize a cost effective smart grid for integrating the renewable resources and for reducing energy losses.

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1. Introduction

A smart grid can be efficiently realized by integrating communication technologies. The smart grid has the ability to communicate with its end devices in real-time that can lead to the efficient integration of RE resources and energy loss reduction. One such communication and sensing network is CRSN that is realized by combining the best of WSNs and cognitive radios.

The cost of WSNs is determined by many factors that include transmission power, processors operating frequency and memory. These networks are deployed in a number of applications including environmental sensing, battlefield monitoring, and forest fire detection [1]. Due to emerging applications, the use of WSNs is expected to increase in future. One of the fundamental requirements of WSNs is to increase the lifetime of resource-constraint sensor nodes. Sending a large amount of data in a timely fashion by WSN requires to send it simultaneously with minimal interference. This leads to higher power efficiency of the overall network. These requirements need to use a cognitive radio network where the abundant resources are used by the wireless sensor node [2].

The technology for cognitive radio (CR) [3–5] is promising for spectrum utilization by providing a technique for power efficiency [6]. This concept was first introduced by Mitola and Maguire [5] to efficiently use the available spectrum. The spectrum which is not fully used by a licensed used (primary user) may be used by the secondary user, without disturbing the primary user. There might be a number of available spectra among the licensed band and the secondary user can access the best available spectrum without causing interference to the primary user. This will increase the spectrum efficiency of the network.

The classical WSN system is characterized by a fixed frequency spectrum [7] and this concept may be used in WSNs for enhancing the network performance. Often a bursty traffic is generated in WSN that increases the chances of collision and the packet loss. Recent works such as Akan et al. [7] propose the application of cognitive radio wireless sensor networks (CRSNs). It is assumed that each sensor node has a cognitive radio. The sensor device selects the best available channel from the available spectrum band and it leaves the channel once the primary user starts its transmission. There might be a number of sensor nodes that may access the same band at the same time. Thus, there is a need for an efficient channel allocation mechanism for all the sensor nodes.

There are a number of new application areas in WSN including medical monitoring and industrial control that may send data at higher rates in real-time. These applications may need to communicate as a secondary user by utilizing a licensed band [8]. For example, smart grids for power systems may be realized using a WSN [9]. There are a number of renewable energy resources that may be used to decrease the overall cost of electricity. There is a need to design an effective control system for efficiently using the generated energy by minimizing the electricity fluctuations and catastrophic events. The key design challenge is to reliably and timely deliver the sensed data using the sensor devices that are installed on various sites so that an efficient decision can be made [10]. In order to meet that challenge, employed WSNs can use the CRSN for realizing a smart grid application.

Based on the above-mentioned discussion, this paper proposes an infrastructure for realizing cognitive radio sensor networks for the smart grid application. Then, a case study is proposed for the implementation of smart grid in Pakistan using the communication coverage data available from the Pakistan Telecommunication Authority.

The paper is organized as follows. Section 2 gives an overview of the electrical and smart grid networks while Section 3 discusses the communication technologies for a smart grid. Section 4 presents an overview of the renewable sources and Section 5 explains the standard classification of WSN. In Section 6, a brief overview of CRSN node architecture is presented. Section 7 proposes the application of CRSN in smart grid networks while Section 9 presents a case study of the proposed smart grid network in Pakistan. Finally, Section 10 concludes the paper.

2. Electrical grid and smart grid

The meaning of smart grid varies for different people who are looking at it from different perspective. In this section, a short overview of conventional power grid is presented. Afterwards, the

new concept of smart grid is presented and it is shown why it can be superior to the existing technologies for power generation and distribution. Finally, some priority areas are identified for the installation of the smart grids that can be realized using wireless sensor networks.

2.1. Basic electric grid system

The electric energy is delivered in real-time to the end system; the power is generated, transmitted and distributed whenever the demand is generated from the end user [11]. The power system normally does not store some where and the demand and supply should be balanced out at a moment. The power is generated at the end system that can be either the renewable resources or the fossil fuel. Then it is converted to high voltage source so that it can be transmitted efficiently for long distances [12,13]. It is then converted into low voltage energy source once it is reached at the distribution point. There it is distributed to the end user which can be commercial, residential or industrial one through its electric meters [14,15]. The distribution system may consist of substations and various components based on the size of the locality and is controlled by the distribution management system (DMS) [12,16,13]. The basic electric grid system is shown in Fig. 1.

Traditional power systems usually consist of two major components, that is, business management system (BMS) and energy management system (EMS) [17,13]. BMS provides features like customer relationship management (CRM) and the billing system while EMS comprises of tools that are useful for an operator to make effective decisions.

SCADA (supervisor control and data acquisition) is an important EMS component that is used to provide monitoring of electrical devices integrated to the EMS system. It is used for monitoring energy flow in various parts of the network such as generation, transmission and distribution and it provides the feedback to the operator present in the control center for taking necessary decisions. However, in this model there is no two way flow communication as there is only uni-directional power flows and the end-user cannot communicate with the electrical grid. It is argued that these grids will be insufficient for the growth in demand of electricity and more efficient control system needs to be developed that can incorporate the inclusion of renewable energy generated by the end-user.

2.2. Smart power grid

One of the important parameter for economic development of a community is the reliable electrical power system. Once more and more power generation sources are locally connected to a local power system then the traditional power systems are not expected to behave in an efficient manner. As this information is not passed onto the central system from the local grid, the existing control system needs to be modified to incorporate these enhancements. The smart grid is based upon the fact that there are a number of renewable energy sources present in a locality and the smart grid has to sense various parameters using an infrastructure of sensors that are communicating with each other. They provide information related to the various parameters needed for effective management of the network. Introducing new features requires a lot of new functionalities to be provided by the end user such as balancing the

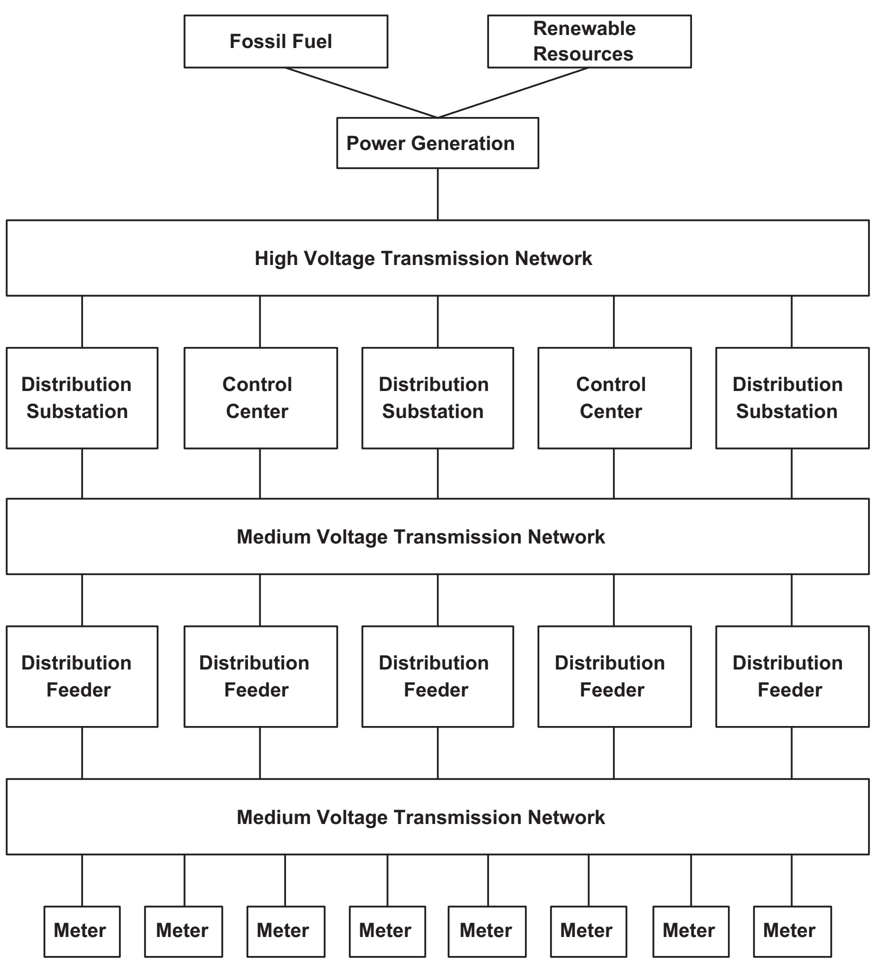

Fig. 1. Conceptual model of electric grid [14].

generation and demand of power at a moment [13]. Thus, it provides intelligent generation and consumption of power by considering the cost and environmental aspects of the power generation.

The definition of smart grid varies among researchers and organizations. The main purpose of smart grid is to communicate the information necessary to integrate the distributed power sources in an efficient manner. A smart grid is a network that is integrated with the electric grid which gathers data related to the generation, transmission and distribution of power and takes the necessary decisions for balancing the demand and supply of the generated power [18,14].

National Institute of Standards and Technology (NIST) in the Smart Grid Interpretability Standards Road map [19] has proposed a conceptual model of smart grid whose top-level abstraction architecture is given in Fig. 2. A more precise model is illustrated in Fig. 3. There is a need to have an inter-domain and intra-domain communication [20,19]. The consumer domain refers to a consumer who can generate, store and use the electricity. The market domain refers to the players available in the electricity market. The operation domain refers to the management of generated electric power. A service provider refers to the organization that generates the electric power. Bulk generation, transmission and distribution explain the generation, transmission and distribution of electric power to the end-user. Thus, the model describes different systems that are necessary for the realization of a smart grid.

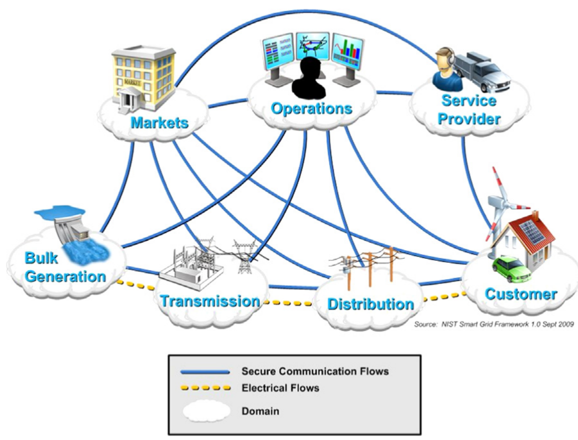

Fig. 2. Conceptual model of smart grid [19].

2.2.1. *Priority areas for smart grid*

Some priority areas have been identified in the NIST document [20,21] that are urgently required from the smart grid are as follows:

1. Demand response and consumer energy efficiency.
2. Wide-area situational awareness.
3. Energy storage.
4. Electric transportation.
5. Network communications.
6. Advanced metering infrastructure (AMI).
7. Distribution grid management.
8. Cybersecurity.

These features can be implemented using CRSN and will be discussed later in the paper.

2.2.2. *Features of smart grid*

The NIST framework shows that the smart grid should support the following features:

1. Information flow (collection, processing and distribution of data).

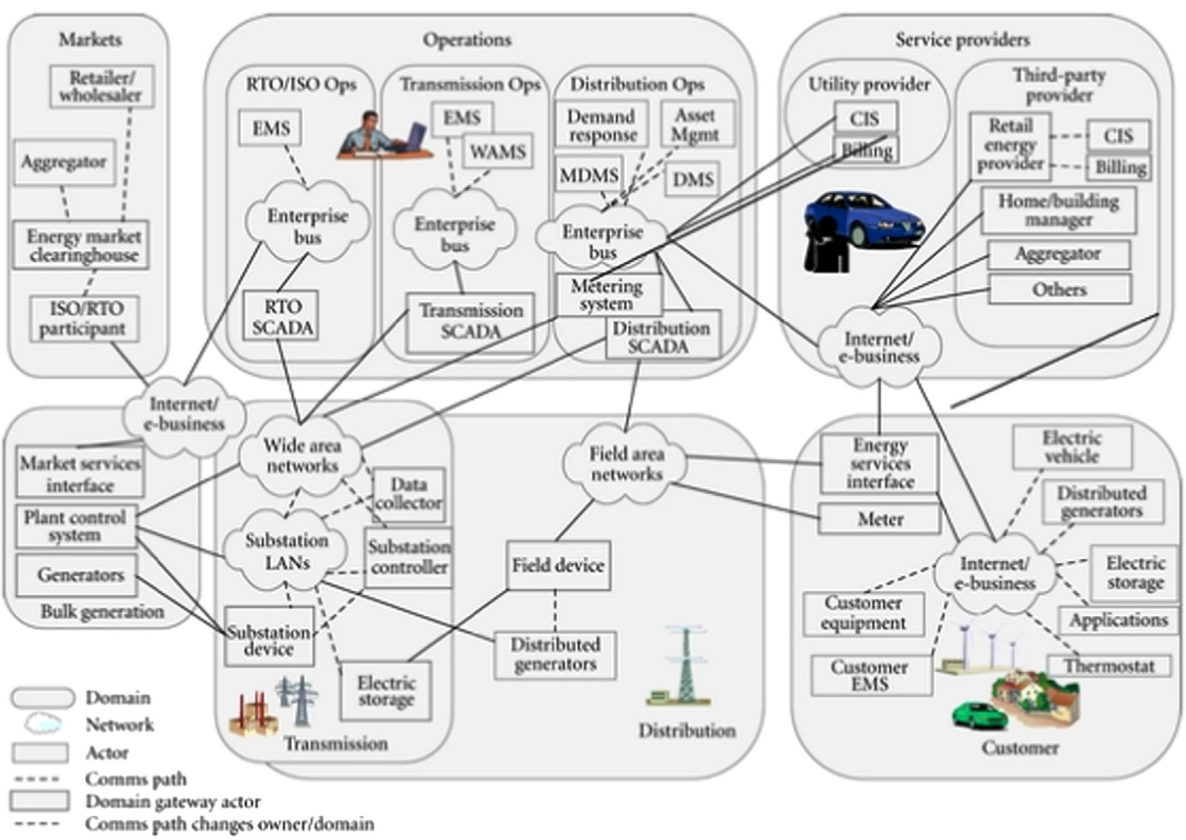

Fig. 3. NIST smart grid framework [19].

2. Electrical flows (generation, transmission and distribution of energy).

The objective of information flow is to monitor and control the flow of energy in the smart grid system. While, the electric flows are currently concentrating on the power delivery, demand and asset optimization. The power delivery optimization includes various efforts for efficient and reliable delivery of power. While, demand optimization targets the assessment of power demand at a particular instant of time. Asset optimization includes the measures to reduce the catastrophic failures of electrical installations.

However, these intelligent functionalities are not provided by modifying the existing grid system. As there is a need of having efficient communication among different entities for cost effective and efficient power delivery to the end-user. Thus, a smart grid has to incorporate feature to integrate the renewable sources and to control the grid.

2.2.3. Requirements of smart grid

The requirements of the smart grid are as follows [14]:

1. *AMI* (*Advanced metering infrastructure*): This is an advanced meter that is used in conjunction with the smart grid and it helps to optimize the usage of power by an end-user [15,22,14]. Using this infrastructure, the consumers know the purchasing patterns based on their needs [23].
2. *Wide area situational awareness*: The use of this part is to monitor and take necessary management decisions of the power system. Such as monitoring the behavior of the end users to avoid catastrophic situations [15,14].
3. *Integration of IT network*: For managing the generation, transmission, distribution and consumption of electric power, a communication infrastructure is needed that needs to integrate the information related to any activity through an IT network.
4. *Interoperability*: The smart grid has the requirement of sharing the information between two or more systems using a secured communication network [14,15]. This will help to make an optimal decision from the devices integrated with the smart grid. The communication of data between different devices should be done in a secure manner [14,15].
5. *Demand response and efficiency of consumer*: There should be a mechanism in smart grids where the end users will cut their power demand during the peak periods. The customers will have different mechanisms that will ensure to smartly use the electric power [14,15]. To implement the features like dynamic pricing and collection of renewable energy generated by the end user, a communication infrastructure along with the computation devices is required.

2.2.4. Key technologies required for smart grid

The following key technology areas have been identified by NETL (National Energy Technology Laboratory) [14,22,23] for implementing a smart grid system:

1. *Integrated communications*: There is a need of duplex, high speed communication infrastructure for the real-time information exchange between various entities of smart grid.
2. *Sensing and measurement*: There is a need to have an infrastructure that measures and transport the necessary physical parameters for having an effective network. This can help in achieving various goals such as prevention of power theft, demand response, and evaluating the protection of Smart grid infrastructure.
3. *Advanced components and control methods*: There will be a need of components that are fabricated after latest research in the areas of power electronics, energy storage and superconductivity. This will help in making the power system more capacitive and reliable. Advanced control methods need to be used to integrate all the newer components into the existing power system.
4. *Improved interfaces*: There is a need to provide improved interfaces to the operator for making seamless and real-time decisions. Also, there is a need to have a decision support system to enhance human decision making.

The peak energy demand of a locality can be met by using the renewable power sources generated at the customer's premises. This requires to have a smart meter that can calculate the power generated by the end-user that is integrated into the power system. The energy generated from renewable sources such as solar, wind and other power sources can contribute up to 10–20% of the peak energy demand. The produced energy can be distributed using a virtual power plant (VPP) [13] by combining the control of various small generating units using a larger one that can be managed by an individual. This idea uses the concept of smart grid for tying together small generating units to form a virtual power source. The unused electric power is sold to the customers using the so-called VPP. Thus, an area can benefit from the use of VPP and smart grid for generating the power from renewable resources that are installed at the customer's premises and the redundant power is sold to other customers. This sort of power policy is being used in a number of developed countries where the governments are facilitating the end user to generate the electricity using a renewable resource at their premises and then sell it to the government using a smart meter [13].

The smart grid heavily depends on the communication infrastructure for its smooth functioning. The following section describes various communication technologies that can be used to meet this requirement.

3. Communication technologies for smart grid

In order to efficiently realize a smart grid network, two way communication is an important key. In this section, various communication technologies for the smart grid network are discussed that can be used in domains such as home area automation and automated metering infrastructure.

3.1. Power line communication (PLC)

In this technology, the modulated signal carrier is introduced over existing power line cable infrastructure for having two way communication. PLC is categorized in narrow band and broadband PLC. The operating band of narrow band PLC is 3–500 kHz with data rates up to 10 kbps. While broadband PLC operates in the 2–250 MHz band with data rates up to several hundred Mbps [20]. The use of either narrow band or broadband PLC depends on the local authorities but the inherent interference and noise issues are present in PLC based communication. This may limit the efficient communication for smart grid applications.

3.2. IEEE 802.15.4 (Zigbee)

IEEE 802.15.4 specifies the physical and medium access control layer for the low-rate wireless personal area networks. Zigbee is based on IEEE 802.15.4 standard and it operates on the ISM bands of 868 MHz, 915 MHz and 2.4 GHz with data rates up to 300 kbps. Since it is operating in the ISM band that is openly available to a number of devices, it can have interference from the neighboring devices. This can limit its application in a smart grid network.

Table 1
Communication technologies for smart grid.

Parameters	PLC	Zigbee	Wi-fi	Cognitive radio
Spectrum choice	-	-	-	+
Interference	- -	- -	-	+
Channel quality	- -	- -	-	+
Transceiver spectrum	Fixed	Fixed	Fixed	Multiple
Energy efficiency	+	+	-	- -
Processing requirements	+	+	-	- -
+ Better performance				
- Medium performance				
- - Low performance				

3.3. IEEE 802.11 (Wi-Fi)

IEEE 802.11 governs the physical and the MAC layer of the Wi-Fi technology. The devices used are plug-n-play and cost-effective. Data rates of up to 54 Mbps can be achieved using this technology. The technology can be used to realize an Internet of Things (IoT) architecture, thus finds its applications in home area networks. However, the reduced channel quality can deteriorate the performance of network.

3.4. Cognitive radio

The technology for cognitive radio (CR) [3] efficiently utilizes the available spectrum. The secondary user can use the spectrum that is not fully utilized by the primary user without causing interference to the primary user. This may increase the spectrum efficiency of the network. For the smart grid, this can be an efficient mechanism as an available spectrum in a given environment that can be utilized; thus decreasing the overall smart grid deployment cost.

Various technologies for smart grid communication are tabulated in Table 1. In this table, + represents an option with better performance, - represents a medium performance option while - - represents a low performance option.

4. Renewable sources

Renewable energy is an important source of electricity generation. These sources can help in generating the electricity without polluting the environment, thus they are gaining interest. One of the modern trend is to connect renewable resources to the smart grid. In this section, renewable energy sources are discussed that can be inter-connected through the smart grid.

4.1. Micro-hydel

Hydro power is a renewable source of electricity and it is quite reliable and clean source of energy. There are a number of projects realized for the hydro power plants. It is clean because after generating the electricity, the water does not become polluted. Thus, it is available for other agricultural uses as well and the dams can prevent the occurrence of floods in a certain region. There are two types of micro-hydel projects, first is the run of river project while the other one is the construction of a dam or barrage. Run-of-river projects involve the installation of turbines on the flowing water while the dams generate electricity from the outwards flow of water. The hydro power plant has simple principles. The potential energy in water is converted to the electricity through the use of turbines in a power station. There is a need to constantly monitor these micro-hydel projects and there is a need to send the data on run-time to the destination. Sometimes, these sources will be near to replace where the communication installation can prove to be costly. In order to properly monitor the sources and here the cognitive radio sensor networks can be used which find their application in such sort of scenario [24].

4.2. Wind

The capacity of wind energy is expected to increase five times in next 10 years [25]. It is one of the most significant source of energy and it has become China's third largest source of energy after hydro and thermal power. However, there are many environmental and economical issues related to the installation of the wind power plants that needs to be resolved.

4.3. Solar

Solar system converts the solar radiations into the electricity and there are two main categories of the solar system: photovoltaic and solar thermal system. Photovoltaic converts solar energy directly into the electricity by a photovoltaic phenomenon while solar thermal uses sun as the heating source and the sunlight is concentrated onto the receiver [26].

Solar technologies basically convert the solar radiations into electrical energy and these technologies can be classified into two main groups, i.e. photovoltaic technology and thermal technology. Solar photovoltaic technology converts solar energy into direct current by the photovoltaic (PV) cells that gather the energy and store it in various storage subsystems. While, solar thermal technologies use solar as a heating source and sunlight is concentrated onto a receiver that uses this energy to heat up the working fluid.

5. Classification of wireless sensor networks

The sensor networks can be used to perform the sensing and communication task in the smart grid. They are classified based on the type of tasks they can perform. In this section, various classes of sensor networks are described that can be used in realizing a smart grid network.

5.1. Wireless multimedia sensor networks

In a classical wireless sensor network, the transmitted information consists of the measured value of a physical parameter such as temperature, pressure, humidity or location of object. It is passed through a low bandwidth and delay tolerant wireless sensor network. However, if the multimedia traffic is to be delivered by a wireless sensor network then there are real-time deadlines associated with the delivery of data [27]. This requires a delay-intolerant, and a large bandwidth network to transport the data to the destination as audio and video streams have to be transmitted by the network. This type of wireless sensor network is called a multimedia wireless sensor network. These devices are fabricated after integrating wireless networking technologies with the cameras and microphones that generate the multimedia traffic which is transmitted by the networking technology. These networks enable the delivery of multimedia streams in real-time that is captured by the heterogeneous sources. These networks have to provide a specific quality of service (QoS) to the application that is running on top of these devices. The other main objective of these devices is to minimize the power consumption of the overall network. Thus design challenges range from ensuring the quality of service by minimizing the power consumption [27]. The conceptual diagram of such a network is shown in Fig. 4.

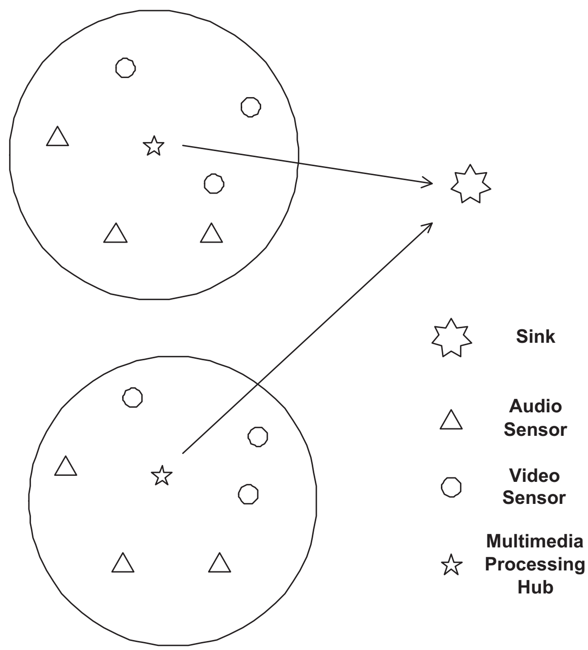

Fig. 4. Conceptual diagram of wireless multimedia sensor networks.

5.2. Wireless underground sensor networks

Wireless underground sensor networks comprise of low power devices that can communicate in underground surfaces. In order to install these devices, these are either buried or placed in an open underground surface. In order to realize a network using these devices, one should know the channel impairments that describe the signal propagation distance. It helps in deploying the network in the real environment. The possible applications include irrigation management, environmental monitoring, mining and border control. Since the communication takes place under ground, there is a need to increase the safety and quality of the communication in the deployed network. The sources of communication can be either electromagnetic (EM) waves or magnetic induction (MI) [28].

5.3. Wireless underwater sensor networks

Underwater wireless communication can help to have control for many applications. There are many applications that can be realized using these networks. It includes commercial, scientific and military applications. In order to realize such applications, there is a need to have an efficient control of underwater devices. There is a specific requirement to implement the application, transport, network, MAC and physical layer of the communication network deployed underwater [29].

The sensor networks described in this section can also be used to implement the priority areas described for the smart grid network. In the next section, architecture of a CRSN node is described that combines the best of sensor networks and cognitive radios. This type of device can implement various applications of the smart grid.

6. CRSN node architecture

CRSN is a combination of a sensor network equipped with a smart transceiver that can detect and use an available spectrum as a secondary user. The transceiver is an important part of the CRSN node as it has to dynamically adapt to various communication parameters such as transmission power, carrier frequency and modulation. The other parts of a CRSN node include a power unit (battery and recharging unit) and a processing unit (processor and memory). A CRSN device for integration with the smart grid can be realized from these components [7]. A block diagram of CRSN node architecture is shown in Fig. 5.

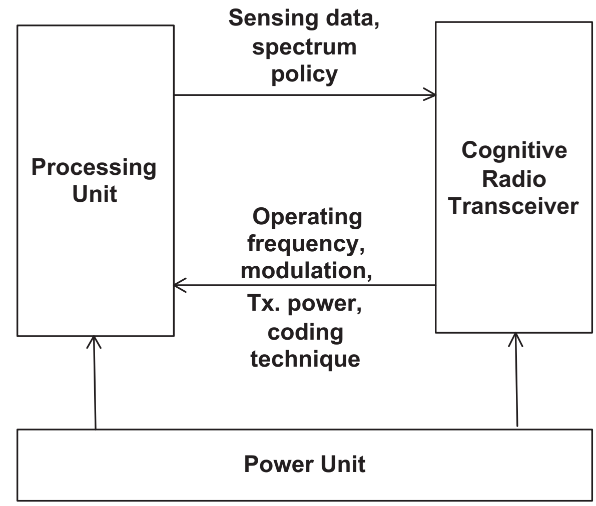

Fig. 5. Block diagram of CRSN node architecture [7].

7. Application of WSNs in the smart grid environment using CRSN

The priority areas described for a smart grid network can be achieved using CRSN. The implementation strategy for the priority areas for the smart grid is discussed below.

7.1. Demand response and consumer energy efficiency

The initiative of smart home helps in minimizing the energy consumption inside a home. It may be implemented as a centralized mechanism for controlling the lights that may reduce the cost of electricity. Smart home can be implemented using sensors to achieve this postulate. The CRSN can be used to remotely control the lights inside a building for achieving efficiency.

7.2. Wide-area situational awareness

Sensor networks using cognitive radio can provide us with the knowledge of area nearby. The knowledge can help in preventing theft of electricity inside a given locality. The people can benefit from the minimization of theft that will ultimately reduce their cost of electricity.

7.3. Energy storage

The generated energy can be stored at some location using feed in tariff program that is a policy mechanism to increase the investment in renewable energy technologies. This program compensates the users that produce the energy from renewable resources and feed it to the national grid. This is stored or consumed by the local smart grid to promote the electricity generated from renewable resources.

7.4. Electric transportation

The power is generated at a remote power plant and afterwards, it is transported to the distribution area using the

transmission lines. During transportation, the lines can be monitored using WMSN and can help in fault minimization. The transmission lines pass through the remote region where the concept of CRSN can help in efficiently monitoring the transmission lines.

7.5. Network communications

It can be realized by cognitive radio technology using the software defined radio (SDR) as it has revolutionized the opportunities in wireless communications [30]. As radio technologies have evolved, the cognitive radio uses the spectrum using a SDR that operates on multiple bands and it can access a spectrum as a secondary unlicensed user. There are a number of platforms that have been realized using SDR for supporting a number of communication standards [31] that can be used for realizing a CRSN.

7.6. Advanced metering infrastructure (AMI)

It is an energy meter that is installed at customer premises for monitoring the flow of energy. It can read real-time energy consumption information and sends it towards a central entity. It can also read the data from the base station, thus it can support bi-directional data communication. The theft can also be prevented by the use of smart meter after integrating a camera with the smart meter infrastructure. The smart meters can be controlled locally or externally and it can be used for the control of home appliances. The smart grid can be used for gathering generation and distribution data from a locality. The customer can generate and feed the electricity to the local grid and the local grid can use this electricity for distribution. The data generated from a smart meter is securely communicated to the destination system using the cognitive radio wireless sensor networks. The customer is billed according to the quantity of energy produced from his premises and the energy used by him from the national grid. The smart meter can help to minimize the theft of electricity at the customer premises by integrating a camera device. The data has to be sent using a multimedia sensor network that has quite high bandwidth requirement [32].

7.7. Distribution grid management

Distributed management can be done for data and can help in many functions such as theft management. This ultimately increases the efficiency of the system.

7.8. Cyber security

The security is an important concept for the implementation of any wireless standard as they are prone to attacks. Recently, there is a focus on the security aspects of cognitive radio network (CRN). The security attacks are classified with respect to the attacker and various solutions are discussed in [33,34] that can be used for realizing data security in CRSN based smart grid networks.

8. Communication technologies for CRSN based smart grid network

As discussed earlier, the communication technology needed for the CRSN can vary based on the availability of a certain service. Based on this knowledge, the issues related with cognitive radios are discussed in this section.

8.1. Cognitive radio sensor networks for smart grid

The sensor networks are usually deployed in a region where they form a network and a sink collects data after some interval of time. However, they communicate through a private network using the zigbee protocol. It is difficult to deploy the network in a remote region where some renewable sources are connected. In that case, the concept of cognitive radio can be used. As discussed in the introduction, cognitive radio uses the existing spectrum as a secondary user on the time slots that are not currently used by the primary user. In that case, a sensor network can act as the cognitive radio sensor networks and it can use the spectrum of the primary user to communicate with the central system in the smart grid network. This provides reliability under harsh environmental conditions. In this case, there is not a need to deploy a network thus the smart grid can be realized efficiently and cheaply. Major advantages for deploying smart grid using cognitive radio sensor networks are as follows.

8.1.1. Efficient spectrum access

The CRSNs can access the spectrum holes available in the network by empowering the cognitive radio equipped sensor networks. Thus, the spectrum is dynamically accessed by the sensor nodes and the best channel is selected for packet forwarding.

8.1.2. Efficient utilization of spectrum

The smart grid network is deployed over a large geographical area and it can use the spectrum holes available in that region. Thus, the unused bandwidth is used by the smart grid devices that are distributed over a large region that increases the spectrum efficiency of the network.

8.1.3. Monitoring of power generation systems

CRSNs can be used for monitoring the power stations as well as the deployed renewable resources. It includes the solar, wind and micro-hydel projects that are deployed in the remote regions as well as in the customer premises. As the cost of deploying a new network for monitoring power generated at customer premises would be significantly high, one of the solution is to install CRSN in that region. Wireless multimedia sensor networks in conjunction with the cognitive radio enabled wireless transceiver would serve the purpose. It can also monitor the safety of staff at a remote station that is generating power.

8.1.4. Remote monitoring of power transmission and distribution system

There is a need to constantly monitor the transmission and distribution lines in order to avoid equipment failure that can result in electricity outage [6]. The transmission lines are deployed for long regions inside a country thus they can be monitored by a CRSN that accesses the available spectrum lying in its way. Not only the spectrum will be efficiently utilized, the network cost would be significantly lower due to the use of available resources. Multimedia sensor networks can be deployed to ensure the security of the network as well.

8.1.5. Monitoring of consumer power generation

The power generated at a certain source can be securely monitored with the help of the CRSNs. Their power demand at a certain time can also be predicted that can be used to balance the generated and consumed electricity by a certain user or community. This helps in efficient power scheduling of the power generation resources. AMI can also be realized using CRSNs that constantly monitor the power in and out at a certain customer premises and generate bill at the end of the month by using the electricity price rate.

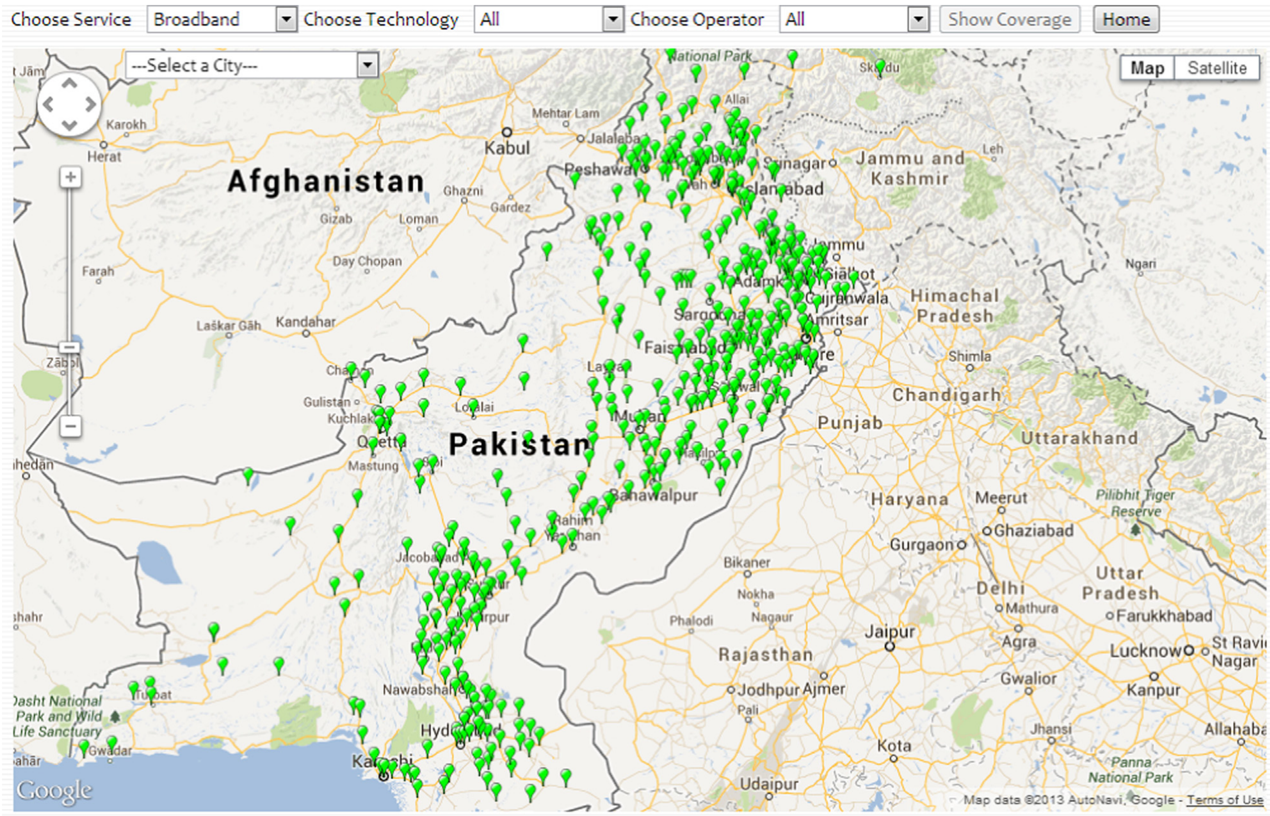

Fig. 6. Broadband connection—service availability map of Pakistan [42].

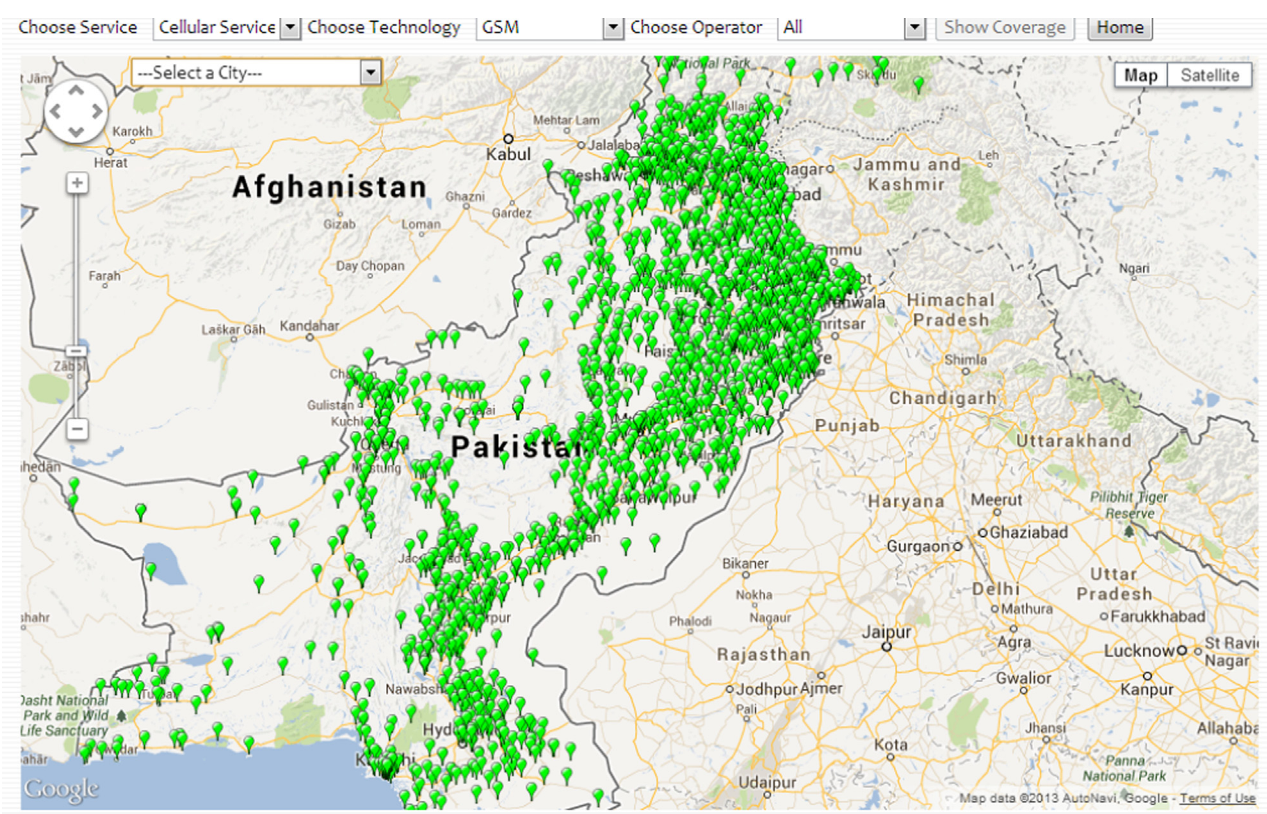

Fig. 7. Cellular connection—service availability map of Pakistan [42].

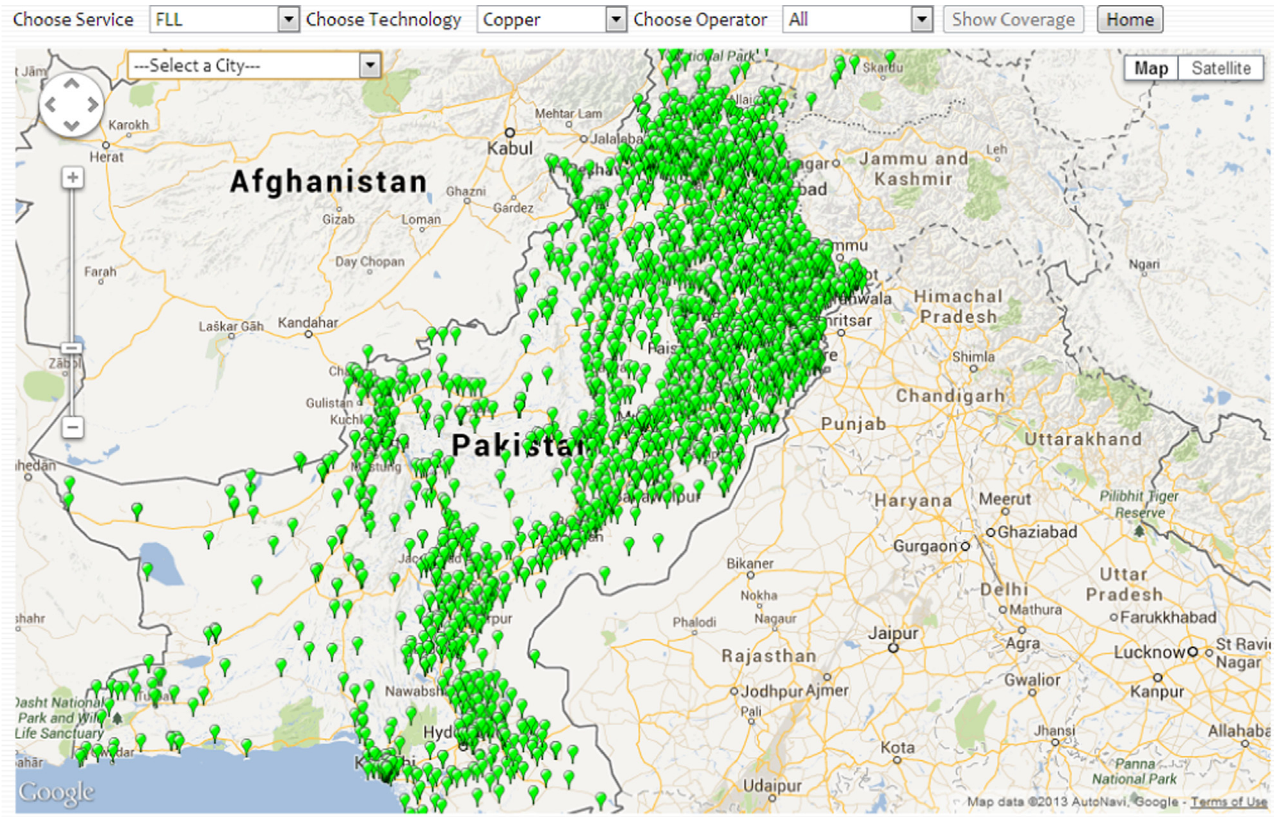

Fig. 8. FLL connection—service availability map of Pakistan [42].

8.2. *Cognitive radio networks – recent work*

Various research directions have been explored for CRSNs in order to minimize the energy consumption of the network. In [35], mechanisms are considered for allocating the received power for secondary user by considering the interference temperature constraint. The pareto optimal solution can be obtained when the entire users' utility function is known that is quite impractical for the distributed system. This problem is extended by considering the quality of service from secondary users and a game is proposed for solving this problem [36].

The performance of cognitive radio networks can be enhanced by employing cooperative communications [37]. In this type of communication, a relay node is used to forward the data of another node to the destination. The diversity obtained by using the relay node can reduce the channel impairments and thus saves the transmission power [8]. Dual hop relaying has been used to study the efficient sensing and networking protocols [38]. While the problem of fair resource allocation in CRSN has been studied in [39].

A large amount of research work has been done on spectrum sharing and channel assignment problem [40,41]. These studies focus on sensing channel availability to make a decision that can improve the network performance parameters such as throughput and delay. However, most of the literature does not consider the energy consumption minimization problem. As discussed earlier, this is an important task for designing a resource constrained WSN for increasing the network lifetime.

8.3. *Downside of CRSN based smart grid networks*

There are a number of advantages for utilizing the CRSN based infrastructure for smart grid networks. However, certain limitations and research problems do exist for realizing such an architecture. The most important is the spectrum sensing as this step helps in making a decision for the channel selection. Various methods to perform the operation include matched filter, energy detection and feature detection [7]. However each method has its own issues. Matched filter requires a priori information of primary user transmissions as well as extra synchronization hardware on user nodes. An energy detection method requires longer sensing duration while feature detection nodes with high computational complexity as well as information about PU transmissions. Most of these methods are not well suited for CRSN as it is a device with limited hardware resources. Thus the CRSN hardware has to meet the following challenges.

8.3.1. *Hardware limitation*

Most of the sensor devices cannot be equipped with sophisticated processors and A/D units. Thus sensing algorithms need to be developed that require minimum hardware resources.

8.3.2. *Sensing duration*

The sensing duration of a CRSN node should be minimum so that a node can perform other useful sensing activities. The operating system of CRSN should be equipped with sophisticated task scheduling algorithms to maximize the benefit out of device by optimally prioritizing the sensing task.

9. Cognitive radio wireless sensor networks for pakistan: a case study

9.1. *Communication infrastructure of pakistan*

The cognitive radio can be used in various parts of Pakistan where there is a need for communication infrastructure installation. According to PTA [42], the coverage of cellular, broadband, WLL and FLL services is installed in various parts of the country.

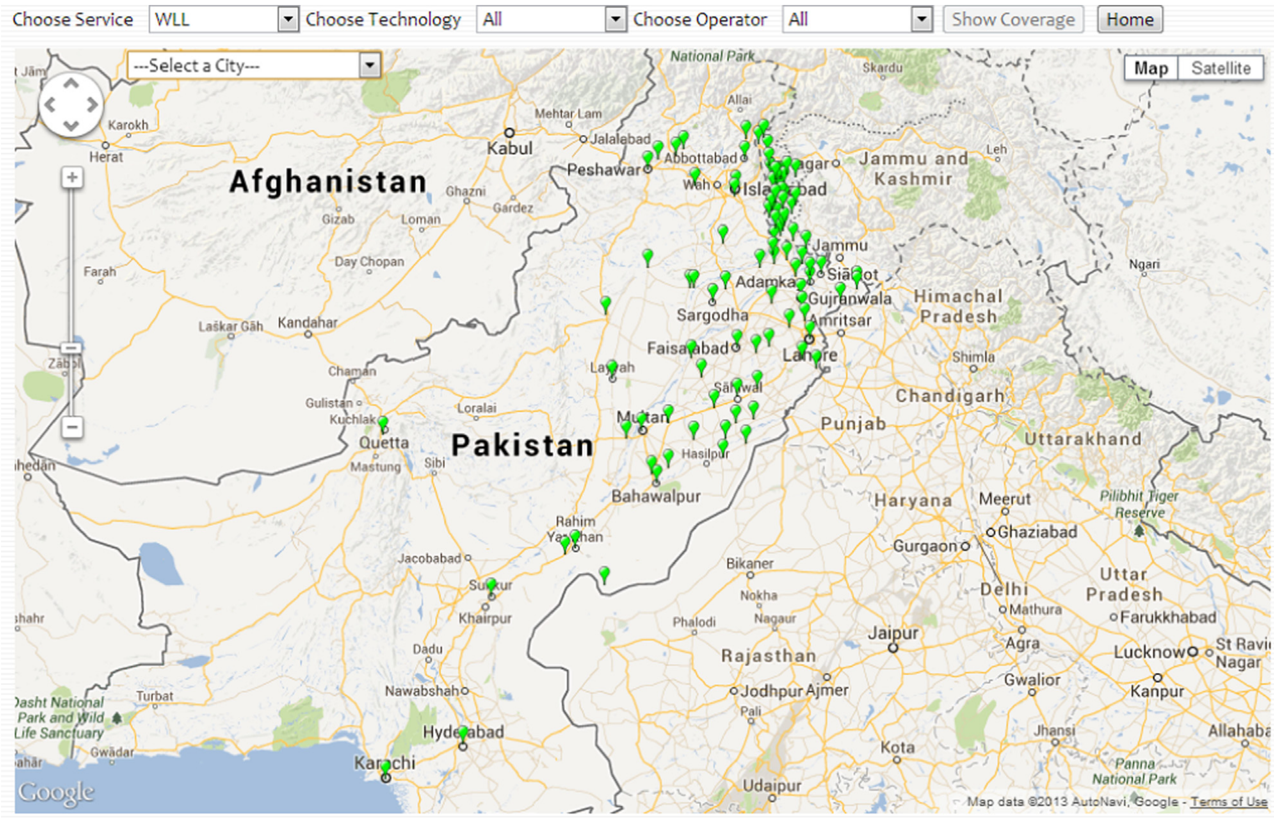

Fig. 9. WLL—service availability map of Pakistan [42].

Fig. 6 shows the broadband map of the country that indicates that various parts of the country have broadband connection available. Also, Fig. 7 shows the cellular map of the country, Figs. 8 and 9 show the FLL and WLL map of the country, however, their coverage is not as much thus they can be used in limited areas. Also, some parts of Baluchistan and KPK provinces have no communication coverage, so these are areas where there is a need to have a particular communication service installation in order to realize a CRSN for smart grids. This communication infrastructure is helpful in realizing a cost effective smart grid network in Pakistan. This will reduce the installation cost of a smart grid network. The other developing countries can also deploy an efficient smart grid using the CRSN technology.

9.2. Benefits of deploying CRSN in Pakistan

The smart grid network coupled with CRSN can help to reduce power theft in Pakistan. According to an empirical study published in [43], 20–25% of generated electricity is lost in Pakistan due to theft and transmission/distribution losses. The overall mismanagement of power sector resulted in accumulated circular debt of Rs. 850 billion (8.6 billion USD) in 2012. On the contrary, the price of software defined radios that can work as a transceiver for CRSN ranges from 10 to 7500 USD [44]. The CRSN can detect the power theft at the customer premises by using sophisticated sensor devices. In order to communicate the data to the central grid, CRSN can use any available network. In the case of energy theft, this arrangement can result in early detection and prevention. If the deployed network is able to reduce the power theft from 25 to 5% each year, then the cost of deployed network (including cost of sensors, transceivers and central grid) can be recovered in nearly 5–10 years. This arrangement will be able to integrate distributed renewable power generation sources using the smart meters. It will eventually help in sustainable production of renewable energy.

10. Conclusion and future work

In this paper, the application of smart grid network for Pakistan is proposed. CRSN can be utilized in the smart grid infrastructure to minimize the cost of the deployed system by using the concept of cognitive network realized using the software defined radio. A brief introduction to the smart grid as well as the electric grid is presented followed by the use of different classes of sensor networks having a software defined radio. It is concluded that these technologies can improve the electricity distribution network in Pakistan. This idea can be deployed in developing countries like Pakistan to have a cost effective implementation of the smart grid.

References

[1] Akyildiz IF, Su W, Sankarasubramaniam Y, Cayirci E. A survey on sensor networks. IEEE Commun Mag 2002;40(8):102–14.
[2] Gao S, Qian L, Vaman DR, Qu Q. Energy efficient adaptive modulation in wireless cognitive radio sensor networks. In: IEEE international conference on communications, 2007, ICC'07; 2007. p. 3980–6.
[3] Haykin S. Cognitive radio: brain-empowered wireless communications. IEEE J Sel Areas Commun 2005;23(2):201–20.
[4] Akyildiz IF, Lee W-Y, Vuran MC, Mohanty S. Next generation/dynamic spectrum access/cognitive radio wireless networks: a survey. Comput Netw 2006;50(13):2127–59.
[5] Mitola III J, Maguire Jr. GQ. Cognitive radio: making software radios more personal. IEEE Pers Commun 1999;6(4):13–8.
[6] Kondo S, Milstein B. Performance of multicarrier ds cdma systems. IEEE Trans Commun 1996;44(2):238–46.
[7] Akan O, Karli O, Ergul O. Cognitive radio sensor networks. IEEE Netw 2009;23(4):34–40.
[8] Pandharipande A, Han Y, Wang Y. Sensing and communication protocols in cognitive sensor relay networks. In: Sensors, 2008 IEEE, IEEE; 2008. p. 617–20.
[9] Gungor VC, Lu B, Hancke GP. Opportunities and challenges of wireless sensor networks in smart grid. IEEE Trans Ind Electron 2010;57(10):3557–64.
[10] Gungor VC, Sahin D, Kocak T, Ergut S, Buccella C, Cecati C, et al. Smart grid technologies: communication technologies and standards. IEEE Trans Ind Inf 2011;7(4):529–39.

[11] Smart grid information report, ⟨http://www.enerweb.co.za/brochures/Smart%20Grid%20Information%20Report.pdf⟩ [accessed 17.07.2013].

[12] Blume SW. System overview, terminology, and basic concepts, in electric power system basics: for the nonelectrical professional. Hoboken, NJ, USA: John Wiley and Sons, Inc.; 2007 http://dx.doi.org/10.1002/9780470185810.ch1.

[13] Markovic DS, Zivkovic D, Branovic I, Popovic R, Cvetkovic D. Smart power grid and cloud computing. Renew Sustain Energy Rev 2013;24:566–77.

[14] Gao J, Xiao Y, Liu J, Liang W, Chen CP. A survey of communication/networking in smart grids. Future Gener Comput Syst 2012;28(2):391–404.

[15] NIST framework and roadmap for smart grid interoperability standards, Release 1.0, January 2010, ⟨http://www.nist.gov/public_affairs/releases/upload/smartgrid_interoperability_final.pdf⟩ [accessed 17.07.2013].

[16] Niemeyer V. Understanding electric utilities and deregulation, second edition [book review]. IEEE Power Energy Mag 2007;5(1):64–7.

[17] Hussain S. Coordination and monitoring services based on service level agreements in smart grids [Ph.D. thesis]. Blekinge Institute of Technology; 2012.

[18] Internet protocol architecture for the smart grid. 2010, ⟨http://www.cisco.com/web/strategy/docs/energy/CISCO_IP_INTEROP_STDS_PPR_TO_NIST_WP.pdf⟩ [accessed 17.07.2013].

[19] Report to NIST on the Smart Grid Interoperability Standards Roadmap, ⟨http://www.nist.gov/smartgrid/upload/Report_to_NIST_August10_2.pdf⟩ [accessed 17.07.2013].

[20] Usman A, Shami SH. Evolution of communication technologies for smart grid applications. Renew Sustain Energy Rev 2013;19(0):191–9.

[21] The NIST Definition of Cloud Computing, ⟨http://csrc.nist.gov/publications/nistpubs/800-145/SP800-145.pdf⟩ [accessed 17.07.2013].

[22] NETL, West virginia Smart Grid implementation Plan, ⟨http://www.netl.doe.gov/energy-analyses/pubs/WV_SGIP_Final_Report_rev1_complete.pdf⟩; September 2009 [accessed 17.07.2013].

[23] NETL. A systems view of the modern grid, ⟨http://www.netl.doe.gov⟩ [accessed 17.07.2013].

[24] Bhutto AW, Bazmi AA, Zahedi G. Greener energy: issues and challenges for pakistan-hydel power prospective. Renew Sustain Energy Rev 2012;16(5):2732–46.

[25] Sahu BK, Hiloidhari M, Baruah D. Global trend in wind power with special focus on the top five wind power producing countries. Renew Sustain Energy Rev 2013;19:348–59.

[26] Khan HA, Pervaiz S. Technological review on solar {PV} in pakistan: scope, practices and recommendations for optimized system design. Renew Sustain Energy Rev 2013;23:147–54.

[27] Akyildiz IF, Melodia T, Chowdhury KR. A survey on wireless multimedia sensor networks. Comput Netw 2007;51(4):921–60.

[28] Akyildiz IF, Stuntebeck EP. Wireless underground sensor networks: research challenges. Ad Hoc Netw 2006;4(6):669–86.

[29] Underwater acoustic sensor networks: research challenges. Ad Hoc Netw 2005; 3(3): 257–79.

[30] Dardaillon M, Marquet K, Risset T, Scherrer A. Software defined radio architecture survey for cognitive testbeds. In: 2012 8th international wireless communications and mobile computing conference (IWCMC); 2012. p. 189–94.

[31] Baldini G, Sturman T, Biswas A, Leschhorn R, Godor G, Street M. Security aspects in software defined radio and cognitive radio networks: a survey and a way ahead. IEEE Commun Surv Tutor 2012;14(2):355–79.

[32] Depuru SSSR, Wang L, Devabhaktuni V. Smart meters for power grid: challenges, issues, advantages and status. Renew Sustain Energy Rev 2011;15(6):2736–42.

[33] Attar A, Tang H, Vasilakos A, Yu F, Leung V. A survey of security challenges in cognitive radio networks: solutions and future research directions. Proc IEEE 2012;100(12):3172–86.

[34] Araujo A, Blesa J, Romero E, Villanueva D. Security in cognitive wireless sensor networks. challenges and open problems. EURASIP J Wirel Commun Netw 2012;2012(1):1–8.

[35] Huang J, Berry RA, Honig ML. Auction-based spectrum sharing. Mob Netw Appl 2006;11(3):405–18.

[36] Nosratinia A, Hunter TE, Hedayat A. Cooperative communication in wireless networks. IEEE Commun Mag 2004;42(10):74–80.

[37] Sendonaris A, Erkip E, Aazhang B. User cooperation diversity. Part I: system description. IEEE Trans Commun 2003;51(11):1927–38.

[38] Akyildiz IF, Lee W-Y, Chowdhury KR. Crahns: cognitive radio ad hoc networks. Ad Hoc Netw 2009;7(5):810–36.

[39] Zhao Q, Swami A. A survey of dynamic spectrum access: signal processing and networking perspectives. In: 2007 IEEE international conference on acoustics, speech and signal processing, ICASSP 2007, IEEE, vol. 4; 2007. p. IV–1349.

[40] Chen Y, Zhao Q. On the lifetime of wireless sensor networks. IEEE Commun Lett 2005;9(11):976–8.

[41] Wang Q, Hempstead M, Yang W. A realistic power consumption model for wireless sensor network devices. In: 2006 3rd annual IEEE communications society on sensor and ad hoc communications and networks, 2006, SECON'06, vol. 1, IEEE; 2006. p. 286–95.

[42] PTA, Pakistan Telecommunication Authority, ⟨http://www.pta.gov.pk⟩ [accessed 17.07.2013].

[43] An empirical study of electricity theft from electricity distribution companies in Pakistan, ⟨http://pide.org.pk/psde/pdf/AGM29/papers/Faisal%20jamil.pdf⟩ [accessed 01.07.2014].

[44] List of Software Defined Radios, ⟨http://en.wikipedia.org/wiki/List_of_software-defined_radios⟩ [accessed 01.07.2014].